Review article

Reinforcement and repair of small sawn *Pinus Sylvestris* beams with carbon fiber

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A B S T R A C T

This paper explores the behavior of wooden beams tested to bending up to fracture, and later repaired with bidirectional carbon fiber fabric of two grammage types, placed in one or two layers. In addition, beams reinforced with the same fabrics were tested to flexural strength until fracture in order to compare the results. For this purpose, 21 beams were tested to bending at 3 and 4 points; 13 of these beams did not have any reinforcement, 8 of them were repaired with carbon fiber reinforced polymer (CFRP) and later tested, and the other 8 beams were reinforced but were not submitted to any previous test. Results show that when the appropriate fabric strength, the repaired beams —previously collapsed— support higher loads than those that initially caused them to fracture.

1. Introduction

Wood is a unidirectional fibrous material, with a radial growth direction. Fibers provide the material with tensile and compressive strength and they are joined by binder elements such as hemicellulose and lignin, lacking any resistance.

Wood is the main construction material for structural elements working to compression and bending in numerous buildings. Deterioration of these structures has brought up, as a consequence, the development of different repair techniques. The most common techniques are the use of reinforcements by means of metallic elements (beams, roofs, etc.) or the replacement of wooden pieces by others in a proper state. In many cases, a large intervention cannot be considered or performed, as buildings cannot remain disused for the long periods required for repair, or there is not enough space to repair them, or the structure has some kind of protection that prevents its replacement. In these situations, composite materials acquire great interest due to their adaptability, speed of execution and high resistance. These three reasons, together with their low weight, have contributed to the widespread use of composites within the industrial sector, in aeronautics, or even in the sports industry [1]. In the construction industry, they are increasingly getting used, as evidenced by the large number of publications related to the topic [2–8], as well as the development of standards and regulations in various construction related areas, such as concrete structures.

It must consider the durability of the FRP strengthening structures. Environmental agents such as alkaline environments, moisture, extreme temperatures, thermal cycles and ultraviolet radiation, may degrade the mechanical properties of the FRP systems [9] and [10]. Glass transition temperature (Tg) is a very important parameter of the epoxy resin used on FRP reinforcement, as it establishes the conditions of service to use this material. Usually, the Tg of the epoxy resin can be placed above 60 °C, although it depends on the manufacturer's characteristics [11–13]. In most implementations, the epoxy is used below of its Tg temperature (i.e., in a glassy state). Generally, when the material is exposed to a hygrothermal environment, the Tg decreases and as a result the service temperature of the material changes. These Tg changes reflect the plastification level of the resin and of water-resin interactions within the material [14]. This should be taken into account in the case of reinforcement beams, because of their hygrothermal properties. For example, an excessive stiffness of the epoxy, with its subsequent inability to sustain the timber strains, especially due to hygrometric variations, can seriously increase the existing cracking state, and even provoke new cracks [15].

Studies of wooden structures reinforced with fibers of polyester (FRP) have mainly focused on the analysis of flexural behavior and shear [16] y [17], obtaining good results in increasing wooden beams resistance and stiffness through different reinforcement configurations [18–22]. The type of reinforcement and its placement can influence reinforced beams final response [23]. Various researchers have tried to solve fracture by shear placing shear sheets on the lateral faces of the beams [24] and [25]. In some cases, beams reinforced with FRP obtained a large improvement of flexural carrying capacity, increasing flexural strength up to 184%, as shown by Kim et al. [26]. De la Rosa [27] obtained, through a U-shaped reinforcement of polyester strengthened with carbon fiber (CFRP) on the face subjected to the loads of timber-sawn beams, a strength increase of 43%, when compared to unreinforced beams.

The use of CFRP reinforcements on beams subjected to bending, not only increases load capacity, but also their ductility. Unreinforced beams ductility is low, and even if wood cannot be considered as a fragile material [28] y [29], the majority of bending fractures occur in loaded face, whose behavior is elastic-linear up to the section exhaustion. Kim et al. [26] achieved good results reinforcing wooden beams with sheets of composite materials, increasing the ductility of beams by 165%.

The majority of works checked analyze the behavior of healthy wooden beams with different configurations of reinforced FRP [30]. Other research works analyze beams that have suffered attacks of xylophagous insects. Very few studies address the mechanical behavior of beams initially collapsed to bending, and later repaired with FRP [31] and [32]. This research study here presents a comparison between the standards governing structural timber [31] and [32], the reinforcements and repairs performed with carbon fiber reinforced polymer (CFRP) —in several layers and grammages— in sawn timber beams subjected to bending in order to check the effectiveness of the repairs and the benefits from the use of carbon fiber (CFRP). Interesting results were obtained for repairs made with completely collapsed beams without any bearing capacity where, in certain cases, they achieved resistance values higher than the ones required by the standard for sawn timber mechanical characterization [33].

2. Materials and methods

To perform the tests, 21 sawn timber beams of *Pinus Sylvestris* from Valsaín (Segovia, Spain) were used, dimensions 1090 × 155 × 80 mm ±2 mm, reinforced with U-shaped CFRP in different configurations to study their response in different situations.

2.1. Visual classification and wood properties

Before carrying out the tests, beams were visually classified according to standard UNE 56.544 [35], getting 13 accepted and 9 rejected. The accepted pieces were assigned a resistant class C-22 based on the UNE EN 1.912:2012 standard [34]. The values of mechanical characterization according to the standard UNE-EN: 338 [26] for class C-22 are indicated in Table 1.

In addition, moisture content tests were performed by drying the samples in a stove, and density was calculated by obtaining the weight and the volume of the pieces, obtaining mean values of 526,36 kg/m^3; and 9.3% moisture content. Beams were collected and tested in the Construction Materials Laboratory of the Technical School of Building Construction of the Polytechnic University of Madrid with an average temperature of 20° ± 2 °C and a relative humidity of 65%.

2.2. Carbon fiber used for reinforcement (CFRP)

The reinforcement material used was bidirectional carbon fiber of 160 gr/m^2 and 210 gr/m^2. In order to characterize fiber, tensile tests were performed to the two types of fiber. The results are shown in Table 2. For gluing CFRP, a two-component epoxy resin was used with a curing time of 5 days. The reinforcement process was carried out by applying a first coat, with a 0.5 kg/m^2 yield, on the beam for fiber bonding. Once the first fiber bonding took place, a layer of epoxy resin was applied for each fiber layer with a 0.3 kg/m^2 yield.

2.3. Experimental tests

In order to verify the effectiveness of CFRP reinforcement applied on beams that had previously collapsed, firstly, timber beams were tested to bending to fracture, and secondly they were repaired with CFRP and tested to fracture. Thus, it would be possible to check the difference between the initial performance (beam without reinforcement) and the repaired beam. Likewise, reinforced beams that had not been previously tested were also tested to check the difference between the new reinforced beams and the repaired ones. By performing this test configuration, the behavioral differences between i) unreinforced wood beams, ii) collapsed and repaired wood beams and iii) reinforced wood beams, could be known.

Bending tests have been conducted at three and four points, placing the beams in a down stand position (Fig. 1), in different configurations (Table 3), to verify the effectiveness of CFRP reinforcement. Thirteen unreinforced beams were tested to flexural strength and 8 beams reinforced with CFRP. Subsequently, 8 of the previously tested unreinforced beams were repaired with 1 or 2 layers of CFRP of different grammage in order to compare the results with reinforced beams. Tests were conducted until total fracture of the beams was produced in all cases. Identification of reinforced and repaired beams corresponds to an X/Y/Z type code created, where: X indicates the beam number (B00); Y indicates the reinforcement type: F: repaired, R: reinforced; and Z indicates the

Table 1
Characteristic values of resistant class C-22 obtained from the UNE-EN 338 standard.

Flexural strength (MPa)	Tensile strength. Parallel to the fiber (MPa)	Compressive strength. Parallel to the fiber (MPa)	Shear strength (MPa)	Elasticity module. Parallel to the fiber (MPa)	Mean density (Kg/m^3)
22	13	20	3.8	10,000	410

Table 2
Characterization values of CFRP used for beam reinforcement.

Fiber type	Fiber layout	Fabric density (gr/m^2)	Fabric thickness (mm)	Tensile strength (MPa)	Elasticity module (MPa)
160	Bidirectional	160	0.04	4757	208,590
210	Bidirectional	210	0.06	4589	197,875

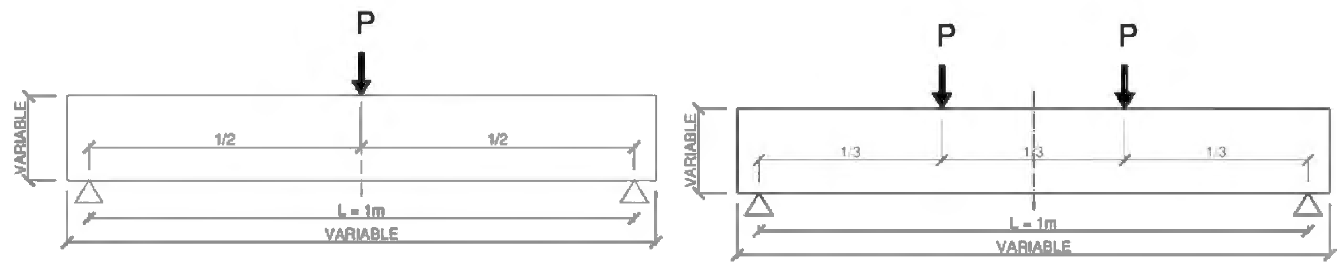

Fig. 1. Scheme of a flexural strength test at 3 and 4 points.

layers of reinforcement and grammage (grammage/layers). Tests were performed in the laboratory of the School of Building Construction of the Polytechnic University of Madrid, using a hydraulic press, model MIB60 Ibertest of 600 kN load capacity, controlling movement at 15 mm/min speed.

A U-shape reinforcement was applied to the face subjected to load (Figs. 2 and 3), reaching up to 75% of the height of the beams side faces to ensure that the damage suffered during bending tests on unreinforced beams had been repaired.

3. Results obtained

3.1. Flexural strength of unreinforced beams

Figs. 4 and 5 and Table 4 show the results obtained in the tests. The first column indicates the beam number; the second column shows the strength class (C-22 or rejection); in the third and fourth column, the maximum flexural strength value reached can be checked, as well as the displacement obtained for that strength value. Fifth and sixth columns indicate the type of fracture and the constraints of it. The ultimate stress value reached by the beam (ultimate fracture stress) has been obtained assuming that the material has a linear elastic behavior, as stated in the Eurocode 5 [36], based on the expression [1].

$$\sigma_{max} = \frac{M_{max}}{W_e} = \frac{M_{max}}{b \cdot h^2/6} \quad (1)$$

In Eq [1]. M_{max} is the maximum bending moment achieved by the beam, W_e is the resistant elastic moment of the section, b is the width of the section and h is the height of the section.

3.2. Flexural strength tests of beams reinforced and repaired with CFRP

Figs. 6 and 8–10 show the results obtained during the bending tests of beams reinforced and repaired with 1 and 2 layers of bidirectional CFRP of 160 gr/m^2 and 210 gr/m^2.

Table 5 shows the results obtained in the flexural strength tests performed on beams reinforced and repaired, and the comparison with unreinforced beams tested to bending.

In Fig. 7, fracture mode of B07-beam and B07F160-1 beam can be seen during their respective tests.

4. Results analysis

4.1. Unreinforced beams tested

4.1.1. Unreinforced beams tested in 4 points bending

Beams classified as C-22 reach higher maximum stress values than those classified as rejected at 4 point bending tests. In addition, the maximum stress values experimentally achieved exceed the values required by the standard UNE-EN 338 [33] for resistance class C-22, to which these beams belong. Fracture patterns respond mainly to 2 different behaviors: i) fracture by shear failure in beams accepted by the standard (resistant class C-22) and ii) fracture by bending failure in beams rejected by the standard UNE-EN 56.544 [35] In case of fracture by shear failure, the absence of defects (knots) prevents the appearance of weak points in the loaded face, avoiding fracturing. Therefore, as the beam supports more loads and greater deformations, becomes unable to absorb the deformations produced in the direction of the fibers, as a consequence of the flexural strength test, which should be assumed by the lignin and hemicellulose arranged for fiber bonding within the wood at a microstructural level. However, such beams lack bearing capacity, and therefore fracture occurs; ii) fracture by bending failure of beams rejected by the standard UNE-EN 56.544. These beams are characterized by the presence of brittle knots in the face subjected to the loads, which implies a fiber cut and, therefore, a weak point that may favor fracture. .

In some of the cases tested (B02 beam), despite of the existence of a knot in the face compressed during the flexural strength test, the beam has been able to reach values accepted by the UNE-EN-338 standard. This suggests that the way wood defects act should be included in the acceptance criteria of the classification standard UNE-EN 56.544. Since the influence of knots on the behavior of wood parts depends on their location, when they appear in the area subjected to the load, they produce a significant weakening, losing

Table 3
Configuration of the flexural strength test performed on the beams.

Beam	Flexural strength test		Beams repaired with CFRP and later tested	U-shaped CFRP reinforcement. Nº layers/grammage of FRP in gr/m^2
	3 points	4 points		
B01		X	–	Unreinforced
B02	X		–	Unreinforced
B03	X		–	2/210
B04		X	–	1/160
B05	X		–	Unreinforced
B06		X	–	Unreinforced
B07		X	X	1/160
B08		X	–	1/210
B09		X	X	1/210
B10	X		X	2/160
B11		X	X	2/160
B12		X	–	1/160
B13		X	X	1/160
B14		X	X	2/210
B15		X	–	Unreinforced
B17		X	X	1/210
B18		X	–	2/160
B19	X		–	2/160
B20	X		X	2/210
B21		X	–	1/210
B22		X	–	2/210

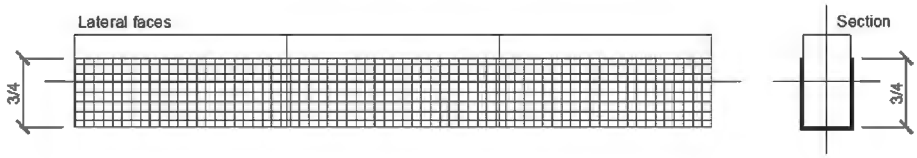

Fig. 2. Scheme of the FRP placing.

section and shunting the fibers; when they are located in the compressed face, stress is transferred through the knot to a great extend, while the impact on the structural behavior of the piece is lower.

4.1.2. Unreinforced beams tested in 3 points bending

Beams follow the same patterns of breaking as those tested in 4 point bending, also exceeding the values set by the standard characterization UNE EN 338 [33]. A reduction in load and displacement capacity can be detected as a result of the shear increase due to the test configuration. This reduction of load and displacement capacity, does not affect the two patterns of breaking previously indicated, so it is worth noting the importance of the presence or absence of defects in the tensile face on wooden beams. In the case of rejected beams, it is detected that beam B02 reaches resistance values above those established by the UNE EN-338 [33] as the knot that marked its rejection was in the compressed beam face, so two aspects stand out: i) under compression, knots affect the mechanical properties of timber to a slight extent; ii) the average resistance of rejected beams tested in 3 point bending increases. Resistance was 14.6 MPa (B20), without the resistance value of beam B02, similar to the rejected beams tested in 4 points bending.

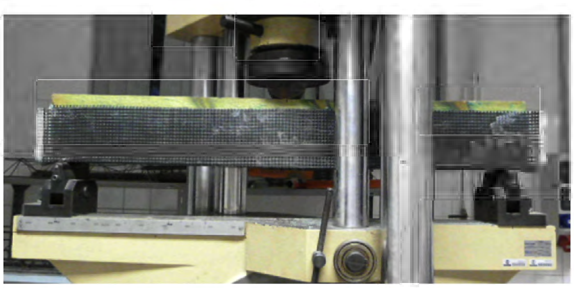

Fig. 3. Flexural strength at 3 points of the beam B03R210-2 with U-shaped CFRP reinforcement.

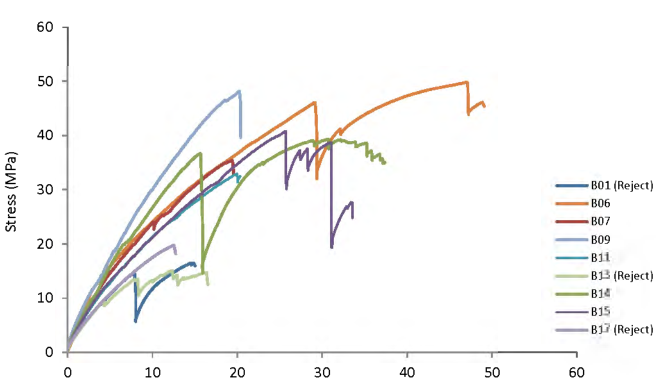

Fig. 4. Stress–displacement of beams without reinforcement tested to flexural strength at 4 points.

4.2. Reinforcement with one layer of bidirectional carbon fiber of 160 gr/m^2

Fracture stress values achieved by repaired beams are well below the mean results obtained in the tests of unreinforced beams. An increase can also be observed in the last displacements in the repaired beams. Repaired beams broke in the same way as in the previous tests, that in this case is shear failure in B07 and bending failure in B13. Beams reinforced with one layer of CFRP of 160 gr/m^2 achieve greater strength and rigidity; even so, their values are below the average ones from unreinforced beams. In this case, fracture occurs by bending failure at the span center in beam B04R160-1 and by shear failure in beam B12R160-1.

4.3. Reinforcement with 2 layers of bidirectional carbon fiber of 160 gr/m^2

B10F160-2 and B11F160-2 beams obtain a very similar strength to the one reached without reinforcement, although their displacement ability increases by 28.7% at the maximum load point. The main fracture mode in both fibers has the same fracture pattern experienced in the previous tests (B10 and B11), which in this case is shear failure in the direction of the fibers. After the main failure in the maximum load point, B11F160-2 beam admits greater loads until the ultimate fracture by bending occurs. B18R160-2 and B19R160-2 beams reach greater values than the reference beams in terms of strength, although with a smaller displacement. In this case both fractures occur as bending failures at the span center.

4.4. Reinforcement with one layer of bidirectional carbon fiber of 210 gr/m^2

B09F210-1 and B17F210-1 beams reach mean strength values very close to those of unreinforced beams and those obtained by beams repaired with 2 layers of CFRP 160 gr/m^2 (F160-2). They also showed greater displacement ability. The two beams fracture in the same place where the previous brake was, which is shear failure in the direction of fibers in the B09 beam, and bending failure in B17 beam. B08R210-1 and B21R210-1 beams achieve higher strength

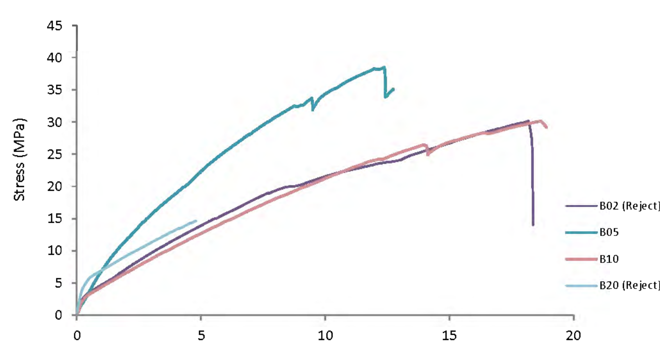

Fig. 5. Stress–displacement of beams without reinforcement tested to flexural strength at 3 points.

Table 4
Results obtained in the flexural strength tests performed in beams without reinforcement.

4 points bending test					
BEAM	Strength class	Max. bending strength (MPa)	Max. displacement. (mm)	Type of fracture	Commentary
B01	Rejected	16.4	17.2	Bending	Presence of knot
B06	C-22	49.7	54.0	Shear	
B07	C-22	35.4	22.3	Shear	
B09	C-22	48.2	23.2	Shear	
B11	C-22	32.9	23,4	Shear	
B13	Rejected	6.8	23.8	Bending	Presence of knot
B14	C-22	39.0	35.2	Shear	
B15	C-22	40.8	29.5	Bending	
B17	Rejected	19.8	14.6	Bending	Presence of knot
Mean results in 4 points bending test					
Accepted	C-22	41.0	31.3	Shear	
Rejected		14.3	18.5	Bending	Presence of knot
3 points bending test					
B02	Rejected	30.1	18.2	Bending	Presence of knot
B05	C-22	38.5	12.4	Bend/shear	Presence of knot
B10	C-22	26.4	18.7	Shear	Presence of split
B20	Rejected	14.6	4.8	Bend/shear	Presence of knot
Mean results in 3 points bending test					
Accepted	C-22	32.4	15.6	Shear	
Rejected		22.4	11.5	Bending	Presence of knot
Mean values of all beams tested in bending					
		30.7	*22.9*		

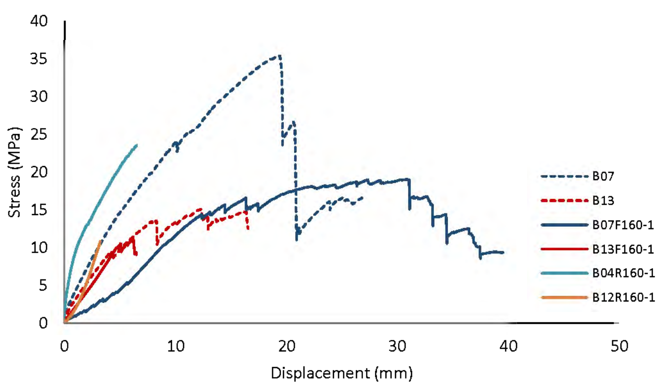

Fig. 6. Stress–displacement of the beams reinforced and repaired with CFRP of 160 gr/m^2 tested in 4 point bending.

and rigidity values than reference unreinforced beams, due to the increase of the elasticity module caused by carbon fiber placement. Beam B08R210-1 suffers shear failure, and the fiber reinforcement is detached from the lateral side of the beam. Beam B21R210-1 suffers bending failure at the center of the span. Both tests show a greater displacement, although this does not imply a total bearing load loss.

4.5. Reinforcement with two layers of bidirectional carbon fiber of 210 gr/m^2

B14F210-2 and B20F210-2 beams obtain higher strength values than those established by unreinforced beams. At the same time, an increase in the displacement capacity is observed. In both cases, the fracture was in the same way that previous beam brakes, which was shear failure in the direction of the fibers. B03R210-2 and B22R210-2 beams reach far greater strength values than those marked by the reference beams. Their displacement ability also increases significantly. B03R210-2 beam fractures at the span center, and B22R210-2 beam suffers numerous shear failures until the final fracture occurs likewise.

4.6. Joint analysis of the beams repaired with CFRP

The analysis of the results obtained allows us to prove that beams repaired with a single layer of carbon fiber of 210 gr/m^2, or 2

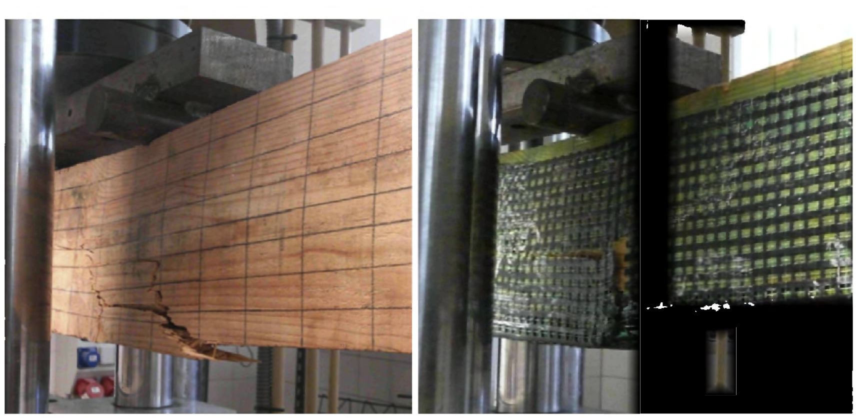

Fig. 7. Beam B07 and B07F160-1 during the flexural test at 4 points.

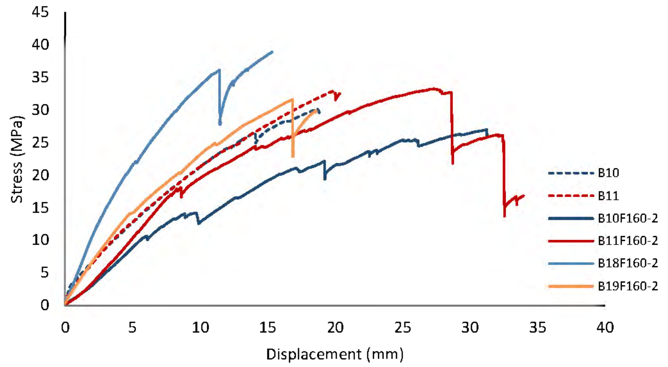

Fig. 8. Stress −displacement of the beams reinforced and repaired with 2 layers of CFRP of 160 gr/m^2 tested in 3 and 4 point bending.

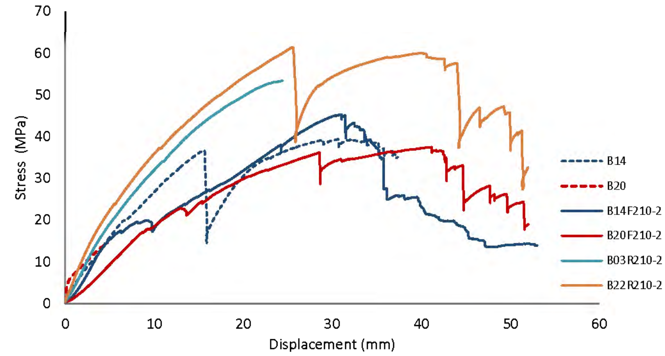

Fig. 10. Stress −displacement of the beams reinforced and repaired with 2 layers of CFRP of 210 gr/m^2 tested in 3 and 4 point bending.

layers of 160 gr/m^2, achieve strength values close to the mean resistance values of unreinforced beams 8.7 MPa higher than the one established in the standard for class C-22 (Fig. 11). When reinforced with 2 layers of 210 gr/m^2, results show a 34.6% higher mean resistance than those of the wood tested. Displacements obtained in all cases exceed the average values of unreinforced beams, increasing in some cases up to 57.6%, which involves more ductile beams. This does not occur in unreinforced beams subject to bending. These results are particularly interesting considering that all the beams tested in this group had no load bearing capacity, as they had earlier been tested up to fracture, and therefore, tensile stresses were entirely absorbed by carbon fiber. For all these reasons, it is worth noting the adaptability of carbon fiber, as well as its suitability to use it with beams that already collapsed and cannot be replaced by new ones. CFRP fractured, in all cases, following the pattern marked by the previous tests of unreinforced beams. This was because, at that point, fiber and wood are not bonded, creating a weak point, and therefore, carbon fiber absorbs all the stresses. In cases in which fracture occurred by shear failure, marking a flush cutting plane between the wood fibers, the beam behaved as two sliding parts, one above the other, breaking carbon fiber on that plane.

4.7. Test analysis of reinforced beams without prior fracture

Strength of reinforced beams depends on the amount of reinforcement placed. Fig. 11 shows a comparison between the mean resistance values and the displacements at the maximum load moment reached by (previously collapsed) repaired and reinforced beams. We can observe that the resistance of reinforced beams is in every case higher than that of repaired beams, and that the displacement of reinforced beams is always lower than that of repaired beams. Reinforcements with one layer of 160 gr/m^2 did not reach the mean resistance values of unreinforced beams. However, with a 2-layer reinforcement of 160 gr/m^2, strength values begin to exceed the average, obtaining a resistance increase between 14.7% and 84.1%, as grammage and reinforcement layers increase. An increase is observed in beams rigidity due to the difference in the elasticity modules −much higher in carbon fiber. The CFRP have caused a regularization of the failures in reinforced beams, increasing the fracture mode by bending failure by 38% (Table 6). It is worth noting that failures produced by bending without reinforcement were caused by the presence of knots, while failures produced by bending in reinforced parts occurred at the center of the span (Fig. 12). This way, fiber acts as a stress regulator, preventing the appearance of the weaknesses that cause fracture. Thus, the failure mode becomes more predictable and controllable.

In some cases, it could be observed that the fiber in the compressed side of the beam detached throughout the test. Therefore, whenever fiber reinforcement has to withstand compression stresses, the correct bonding between the specimen interface/reinforcement should be ensured, since fiber detachment can cause greater delamination, as it might drag the rest of the fiber affecting the reinforcement of the loaded face, rendering reinforcement useless (Fig. 13).

5. Conclusions

The presence of defects in the loaded side provokes fracture by bending in the beams. Pieces without significant defects make a

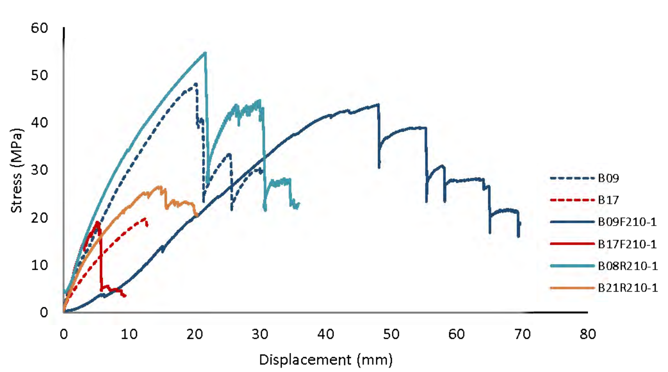

Fig. 9. Stress−displacement of beams reinforcement and repaired with one CFRP layer of 210 gr/m^2 tested in 4 point bending.

Table 5
Comparative values between flexural strength tests performed on beams reinforced and repaired in their different configurations and previous reference configurations, with the mean values obtained in the bending tests of all unreinforced beams.

		Stress (MPa)	Max. Disp. (mm)	Stress (30.7 MPa)	Max. Disp. (22.9 mm)
Reinf.	Reference	26.8	18.6	−12.7%	−18.6%
210-2	F210-2	41.3	36.1	+34.5%	+57.6%
	R210-2	56.5	24.9	+84.1%	+8.5%
Reinf.	Reference	33.9	16.4	+10.6%	−28.5%
210-1	F210-1	31.4	26.6	+2.4%	+16.3%
	R210-1	40.6	18.3	+32.2%	−20.2%
Reinf.	Reference	30.8	19.5	+0.3%	−14.7%
160-2	F160-2	29.9	29.5	−2.7%	+28.7%
	R160-2	35.2	16.1	+14.7%	−29.7%
Reinf.	Reference	25.3	15.9	−17.7%	−30.7%
160-1	F160-1	15.1	18.5	−50.8%	−19.1%
	R160-1	17.2	4.9	−44.0%	−78.6%

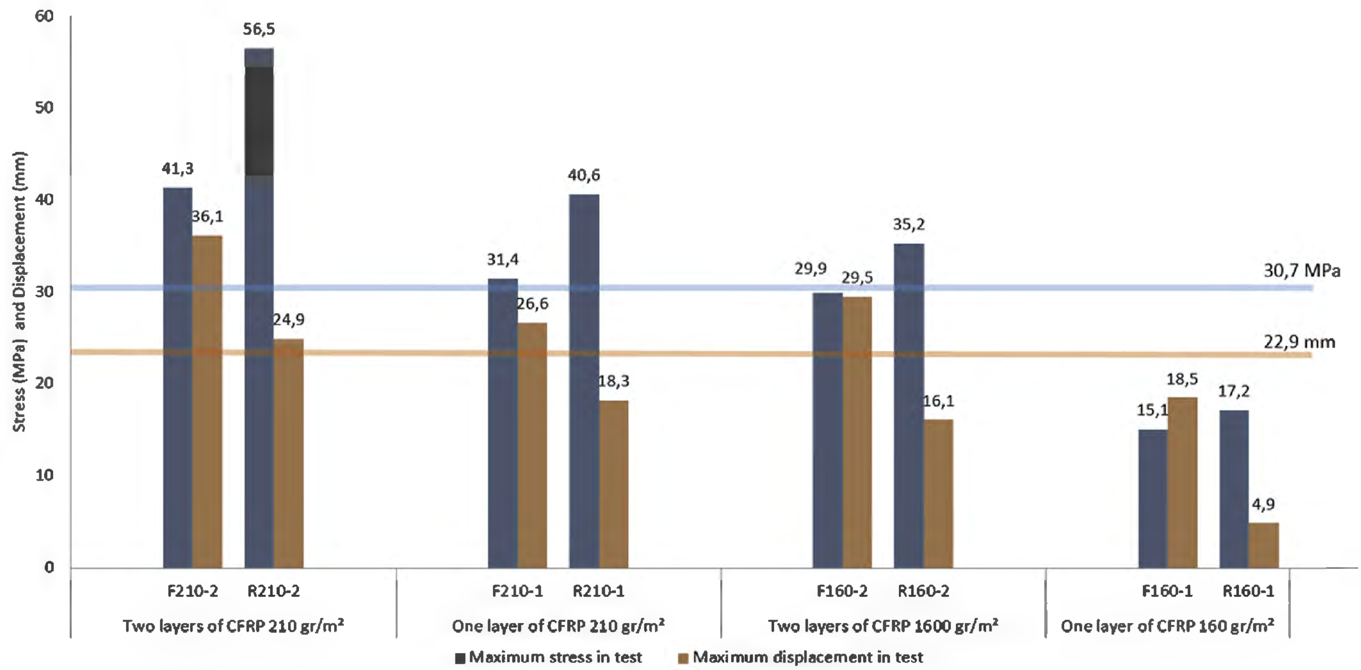

Fig. 11. Comparison between repaired beams, reinforced with bidirectional CFRP, and the mean values obtained in the bending tests performed on all unreinforced beams.

Table 6
Percentage of the main fracture modes in the flexural strength test of beams with and without reinforcement, not having been tested earlier.

	Bending	Shear	Flex/Shear
Beams without reinforcement	38%	47%	15%
Reinforced beams	75%	25%	

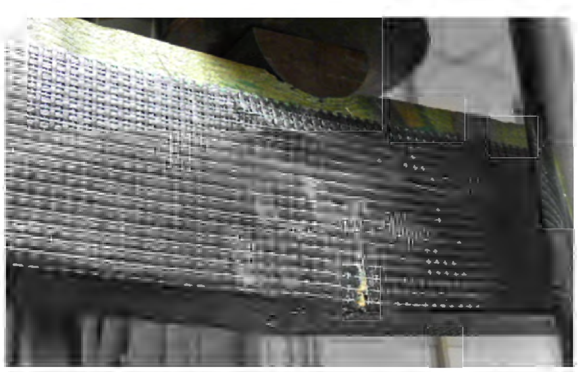

Fig. 12. Fracture by bending failure of beam B03R210-2 during the flexural strength test at 3 points.

flush cut shear in the direction of the fibers.

Reinforcement and repairs with CFRP of 160 gr/m^2 did not produce good results, even if we observed that, with a sufficient amount of CFRP, it is possible to recover and even increase the initial resistance of beams. A more extensive experimental program must confirm these results.

A 2-layer reinforcement of 210 gr/m^2 obtained a resistance increase of 34.6% in repaired beams and of 84.1% in reinforced beams

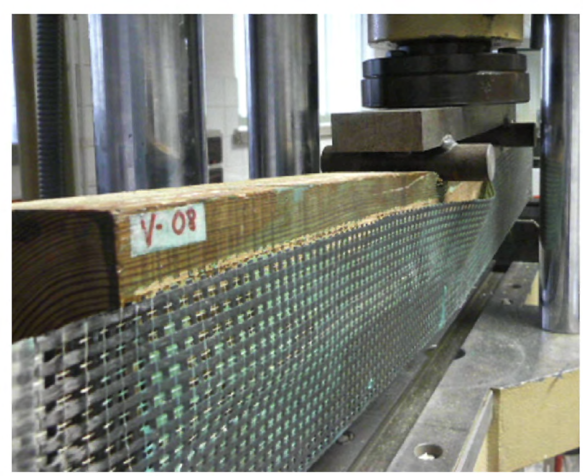

Fig. 13. Delamination of carbon fiber in beam B08R210-1 during the bending test at 4 points.

when compared with unreinforced beams; this fact appears to be especially interesting.

Carbon fiber absorbs specific critical stresses caused by wood defects. Thus, a regularization of wood heterogeneity is reached, together with a decrease of shear fractures, therefore increasing bending fractures.

Beams reinforced with CFRP become more ductile than those unreinforced due to their capacity to keep bearing loads after the first wood fracture.

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